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Condensation or "Sonic" puffs

by

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Reports have been received from time to time of the appearance of puffs of vapour when an aircraft approaches or exceeds the speed of sound. The puff occurs on less than 50% of occasions, and its persistence when formed is very variable. It may take the form of a vortex ring. Some controversy has arisen among observers of the phenomenon whether the puffs occur only as the aircraft accelerates through the speed of sound or whether it is merely a high-speed effect. Thus in correspondence in "Flight" Yates (1) regards the puffs as short contrails viewed end-on but an observation by Harrison (2) makes it appear that the puffs had an origin different from that of a contrail. On the occasion described a Sabre aircraft was observed making a single contrail at about 30,000 ft.; it then went into a vertical dive with a contrail still being formed until at about 25,000 ft. the contrail stopped. As the aircraft began to pull out of its dive at about 18,000 ft. two bluish-white puffs of vapour whipped off the wings and nose and these puffs remained in existence for several hours. A sonic bang was heard indicating that the aircraft had attained the speed of sound.

There seems little doubt that the puff is a condensation phenomenon associated with the development of areas of low pressure on the wing surface and consequential adiabatic cooling of the air below its dew point. Flight and wind tunnel tests (3) show that this reduction of pressure may be substantial and increases with the speed of the aircraft up to a Mach number of about 0.90 for zero overall lift coefficient. Although measurements have not been made at speeds much in excess of Mach 1.0 there appears to be some evidence that the maximum pressure reduction occurs very close to the wing tip at a speed of about Mach 0.93 for the P.1052 but at a speed of about Mach 1.07 for the DH.110 aircraft. The reduction of pressure is further increased by a change to climbing attitude. The pressure measurements are made at orifices in the skin of the wing and it is not known to what extent these measurements reflect the pressure distribution in the air more than a few inches above the wing surface. For this reason the magnitude of the adiabatic cooling deduced in the following paragraphs and in Figs. I and II must be regarded as the maximum possible cooling which may only affect a very thin layer of air as it traverses the wing. At a speed corresponding to Mach 0.93 the cooling of the air towards the tip of the wing of the Hawker P.1052 aircraft may amount to about 15 per cent of the ambient air temperature with zero lift coefficient increasing to about 17 per cent if the angle of incidence of the fuselage to the airstream changes to 2.0° (lift coefficient 0.16). The temperature reduction in the air near the surface of the wing deduced from the pressure reductions is shown Figs. I and II for an ambient temperature of 250°A and a Mach No. of 0.93 for overall lift coefficients of zero and 0.16 respectively. Cooling of the air of the magnitude shown would very frequently lead to condensation in the troposphere and in fact on many occasions condensation would be expected to occur in the air over a large part of the wing surface. That this does occur at low levels on some occasions of high humidity has been noted by ground observers watching high speed flights when the aircraft appeared to be almost completely surrounded by vapour.

/With

With zero lift coefficient however this condensation phenomenon is likely to be short-lived and confined to a small volume of air close to the part of the aircraft wing where the pressure reduction is great enough; for as is shown in (3) immediately after suffering a reduction in pressure the same air is compressed again as it flows back across the aircraft wing and will be suffering compression to greater than ambient pressure before leaving the trailing edge over the whole wing, even at high subsonic speeds (e.g. Mach 0.93). If, however, the aircraft attitude is changed leading to an increased lift coefficient, as, for example, at the pull-out from a dive then, for the P.1052, by the time the angle of incidence is increased to 2.0° (lift coefficient 0.16) the pressure remains reduced below the ambient pressure towards the wing tip even at the trailing edge at Mach 0.93. At greater angles of incidence this reduction of pressure at the trailing edge increases for the same Mach number and spreads further along the wing from the wing tip.

Thus at high Mach numbers when the aircraft attitude is changed the air close to the whole of the wing tip (upper and lower surface) will be at reduced pressure and quite likely to be saturated. Furthermore since the change of attitude is sudden and presumably short-lived as well as accompanied by a change from descent to climb it is possible at the instant of change to visualise an isolated vortex containing saturated air being projected from the wing tip of the aircraft into undisturbed air beneath the aircraft. It seems possible that the recovery of pressure in the vortex centre may be slow enough on some occasions for the air to remain saturated for a few seconds at the centre of the vortex and thus lead to the appearance of a puff of vapour. A condition favourable to this would be particularly non-turbulent air of high relative humidity. The likelihood of occurrence and persistence of the puff would be increased if the fall of temperature at the centre of the vortex was such that ice crystals were formed in the air, since these ice crystals would be able to persist when the air returned to normal pressure if the air temperature was below 0°C and if the air was supersaturated with respect to ice although not saturated with respect to water. This would require a cooling of the air in the cast-off vortex to below about - 40°C, which from Figs. I and II is clearly a possibility for ambient air temperatures in the region of 250°A.

This seems the probable explanation of the experience quoted above when the puffs remain visible for several hours, although without detailed observations by the pilot and from the upper air in the region of the occurrence there is no possibility of verification. A somewhat different explanation can be derived from the observations reported by Lukasiewicz (5). He assumes that on some occasions the adiabatic expansion of the air can be so rapid, and exist for so short a time, that an insignificant amount of condensation occurs on the normal condensation nuclei present in the air and by far the greater amount occurs on nuclei formed by the chance aggregation of water molecules by collision. This theory is used to explain "condensation shocks" which occur in wind tunnels and nozzles at very high speeds and it is possible that the expansion of the air as it flows over the wing at near-sonic speeds is also too rapid for normal condensation to occur. For the occurrence of a sufficiently high number of such "molecular condensation germs" for visible cloud to be formed a high degree of supersaturation is needed and it can be shown that practically no condensation is possible in this way unless the adiabatic cooling is of the order of 40°C in air described as "of normal temperature and humidity". Figs. I and II indicate that cooling of about 40°C may be reached in the pull-out from a dive at high Mach No. over a limited part of the wing tip and may therefore lead to the appearance of a puff of vapour in a similar way to that explained above.

Whatever the mechanism of condensation the necessary conditions for the appearance of a puff would appear to be:-

(i) High speed

(ii) Change of attitude of the aircraft

(iii) Non-turbulent air at the height where the puffs appear

(iv) High relative humidity and for persistent puffs the ambient air should be at a temperature below 0°C and at least saturated with respect to ice.

/Whether

Whether it is necessary for the aircraft to achieve supersonic speed seems doubtful since wing tip trails have been observed with relatively slow aircraft (4) in particularly favourable conditions; one possibility is that if the vortex leaves the aircraft at supersonic speed it will initially be travelling in air undisturbed by any compression wave from the aircraft and hence be more able to retain its identity. The change of attitude of the aircraft, however, may be sufficient to ensure this.

It should be emphasised that no detailed observations at the time of occurrence of these puffs were available to the writer although some may have been made by the test pilots attached to the aircraft firms. If further investigation is considered necessary a request should be made for pilots on high speed flights to note the relevant details on occasions of occurrence and on occasions when puffs may have been expected but did not occur.

Acknowledgments

This report has been based on information and publications supplied by Messrs. Warren and Naysmith, Aerodynamics Department, R.A.E. and Mr. Murgatroyd, M.R.F.

References

(1) Yates: Correspondence in "Flight" for 9th October, 1953.

(2) Harrison: Correspondence in "Flight" 6th November, 1953, p. 626.

(3) Collingbourne, J.R. and Pinder, A.C.S. : Technical Note No. Aero 2221, February, 1953. Restricted.

(4) Meteorological Office: Condensation trails from aircraft. M.O.479, H.M.S.O., London, 1946.

(5) Lukasiewicz, J. : Humidity effects in supersonic flow of air. R.A.E. Report No. Aero 2211. S.D.20. Restricted.

ADDENDUM TO M.R.P. 864

Since the above was written the author and Mr. Murgatroyd (M.R.F.) have had the benefit of a discussion with Messrs. Küchemann, Naysmith and Warren of the Aerodynamics Department, Royal Aircraft Establishment. From the discussion it would appear that less importance should be attached to the pressure distribution on the wing surface since at very high speeds the airflow may become detached from the wings over part of the wing-span leaving a boundary region of dead air. Pressure measurements on the surface in these conditions are not necessarily typical of the pressure changes in the air flowing over the wings. The pressure distribution most required is that in the wake of the aircraft immediately behind the wing but this volume has not yet been explored except in the early wind-tunnel experiments of Fage and Simmons (6) at low wind speeds.

During a high speed dive the lift coefficient is about zero until the pull-out is commenced. During the pull-out, which may take several seconds to perform, the lift coefficient may rise to 0.5 or more so that the effects illustrated in Figures I and II would be greatly enhanced. It is not difficult therefore to envisage vortices shed from the wing with sufficiently low central pressure and temperature to give condensation but difficulty arises when considering the discontinuous nature of the phenomenon. If the pull-out is smoothly executed and lasts several seconds one might expect to observe a trail or series of puffs perhaps a mile in length, rather than a single puff and no explanation can be offered for the isolated nature of the occurrence.

It is to be expected that in the course of time more detailed observations of puff occurrences may be made, although the pilot is unable to observe their occurrence, and in the meantime a satisfactory solution of the phenomenon awaits a more detailed knowledge of the vortex distribution in the wake of a high speed aircraft. A suggestion by Dr. Küchemann (see also ref. (7)) that a water tunnel may be more useful than a wind tunnel in investigating the wake is of interest.

References

(6) Fage, A. and Simmons, L.F.G.: An investigation of the airflow pattern in the wake of an aerofoil of finite span. Aero.Res. Council R. & M. No. 951, 1925.

(7) Küchemann, D.: Types of flow on swept wings. Journal R. Aero. Soc., Vol. 57, p. 683, November, 1953.

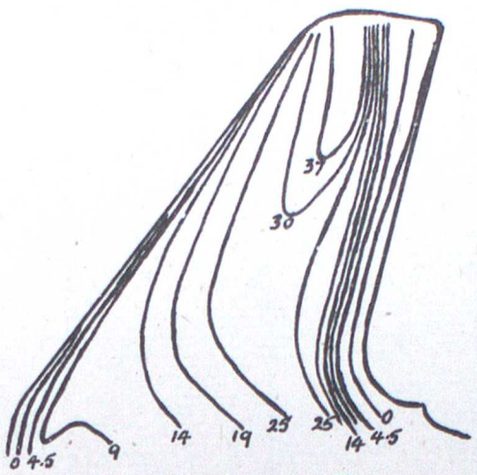

Fig.I. Temperature reductions (°C) in air near surface of wing of P.1052 aircraft in ambient temperature of 250°A at speed of Mach 0·93 ~ overall lift coefficient zero.

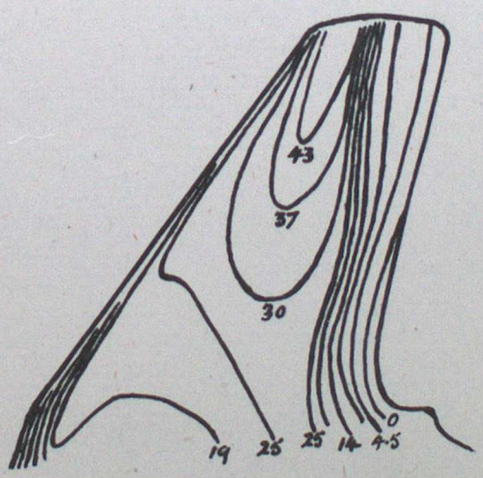

Fig. II. As Fig.I. for overall lift coefficient of 0·16